High-Frequency Sound Interaction in Ocean Sediments: Modeling Environmental Controls

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LONG-TERM GOALS

Our long term goal is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow water ocean sediments. This work should specifically improve the Navy's ability to detect buried mines and, in general, improve sonar performance in shallow water. Additional objectives of the NRL program are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

OBJECTIVES

Provide statistical characterization of the environmental properties, especially the roughness and sediment volume properties, required to determine and model the dominant mechanisms controlling the penetration of high-frequency acoustic energy into the seafloor. Determine the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial and temporal distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site. Develop predictive empirical and physical models of the relationships among those properties.

APPROACH

The "High-Frequency Sound Interaction in Ocean Sediments" DRI addresses high-frequency acoustic penetration into, propagation within, and scattering from the shallow-water seafloor. The primary goal of the proposed study is to understand the mechanisms for high-frequency acoustic energy penetration into sediments at low grazing angles. At present, three mechanisms are hypothesized to contribute to subcritical acoustic penetration. First, the porous nature of the sediment leads to a "slow" wave with a speed less than the speed of sound in water; thus no critical angle for that converted wave exists (Chotiros, 1995). Second, seafloor roughness diffracts energy into the sediment (Thorsos et al., 1997). Third, sediment volume heterogeneity scatters the evanescent wave energy that propagates along the seafloor interface into the sediment (Maguer et al., 2000). In order to compare the predictions of

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14. ABSTRACT
Our long term goal is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow water ocean sediments. This work should specifically improve the Navy’s ability to detect buried mines and, in general, improve sonar performance in shallow water. Additional objectives of the NRL program are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

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penetration of high-frequency acoustic energy into sediments based on these three hypotheses to actual data, seafloor roughness and the spatial variability of sediment physical and geoacoustic properties must be characterized.

If the high-frequency acoustic bottom interaction models are to be utilized outside specific experimental conditions, the effects of environmental processes (biological, hydrodynamic, geological, and biogeochemical) on the spatial and temporal distribution of properties that control propagation, scattering and penetration phenomena must be understood (Richardson and Briggs, 1996). NRL, working with other DRI investigators, quantified and are modeling these relationships. It was found that that short-term biological modification of surface roughness and long-term hydrodynamic modification of sediment morphology and roughness were the dominant environmental processes controlling seafloor properties at the experimental site. For the field experiment (SAX99), the Applied Physics Laboratory-University of Washington (APL-UW) coordinated the overall experimental design with considerable input from the other DRI scientists. APL-UW and Applied Research Laboratory-University of Texas developed the acoustic sampling strategy and the Naval Research Laboratory coordinated site selection with DRI investigators and developed an environmental sampling strategy. Scientists from NRL and APL-UW concentrated on temporal changes in acoustic scattering by modifications of seafloor roughness and the addition of discrete scatterers (shells and marbles) to the seafloor.

WORK COMPLETED

The SAX99 experiments were conducted in October-November 1999 (FY00) near Destin, Florida. Pre-site surveys were conducted in August/September 1998 and June/July 1999. The publication of Richardson et al. (2001) and Thorsos et al., (2001) provide detailed descriptions of the preliminary results and demonstrate that NRL completed all of its proposed objectives. Detailed analysis of experimental results will be presented in a second special issue of IEEE Ocean Engineering (Eric Thorsos and Mike Richardson, guest editors) to be published in early 2002. Among the environmental tasks completed are:

- Developed, tested and conducted resin impregnation techniques to provide values of pore size, pore throat length, permeability, and tortuosity parameters
- Developed, tested and conducted techniques to measure grain bulk modulus
- Developed an environmental data acquisition strategy that, in conjunction with the acoustic measurements, acquired data we believe is sufficient to separate penetration hypotheses
- Provided statistical characterization of the environmental properties required to determine and model the dominant mechanisms controlling the penetration of high-frequency acoustic energy into the seafloor with an emphasis on subcritical angles in sand and to improve our understanding of high-frequency bottom scattering
- Conducted (with APL) a series of manipulative seafloor experiments to determine the effects of discrete scatterers (shells and marbles) and induced roughness on scattering of high-frequency acoustic energy from the seafloor

- Measured the temporal effects of biological and physical (hydrodynamic) processes of seafloor roughness and high-frequency acoustic scattering

- Measured both high- and low-frequency sound speed and attenuation to better understand dispersive behavior of acoustic propagation in sand sediments.

- Collected and analyzed sediments, using in situ techniques, to provide the least-disturbed sediments for characterization of pore-grain relationships.

- Completed analyses of data collected during SAX99 including roughness data, laboratory experiments, and microstructural studies of resin-impregnated cores

RESULTS

The SAX99 results indicated that the presence of sediment interface roughness, and the decay and modification of the roughness over time, controlled the backscattering strength from the sea floor. From diver-operated, underwater photogrammetry, we assessed the 1-dimensional roughness spectrum at two sites and at various times during acoustic experiments. Seafloor roughness was characterized by a sand ripple field with the strike of the ripples roughly parallel to the east-west trend of the coastline. Stereo photographs were collected from BAMS and STMS sites at times and in orientations specified in Table 1.

Table 1. Roughness power spectrum slopes and intercepts as functions of time. A major storm event occurred on 8-9 October and elapsed time is relative to the event.

Site	Date	Elapsed time *re* storm event (d)	Azimuth of profile	Spectral slope	Spectral intercept (cm^3)
BAMS	5 Oct.	-3	N	-3.16	0.00064
	19 Oct.	10	N	-2.73	0.00096
	23 Oct.	14	NNE	-2.54	0.00077
	5 Nov.	27	NNE	-2.53	0.00071
STMS	4 Nov.	26	NNE	-2.44	0.00117
	4 Nov.	26	SE	-2.47	0.00126

There was a general tendency for power spectral slopes to become less steep and reach a stable value near –2.4 to –2.5, which, because of only a small change in the high-spatial-frequency portion of the spectrum (indicated by the spectral intercept in Table 1), was a consequence of changes in the low-spatial-frequency portion of the spectrum. The temporally variant slope of the roughness spectrum was a manifestation of smoothing of recently generated, sharp-crested ripples by biological activity and wind-wave currents to subtle, undulating features only reminiscent of ripples (Fig. 1).

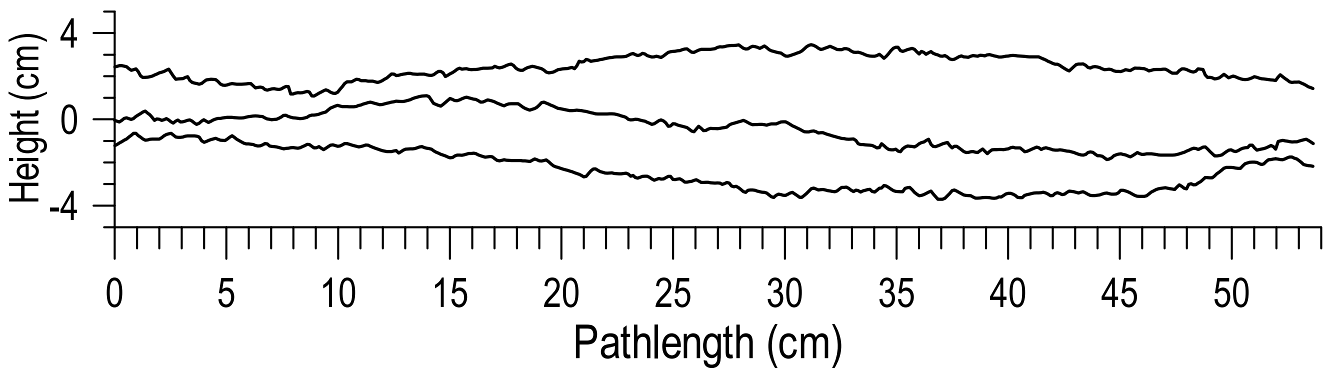

Figure 1. Three 2-dimensional profiles of seafloor roughness at the BAMS site on 23 October 1999.

The high-frequency components of the three 2-dimensional profiles in Fig. 1 are a consequence of surface trails created by small invertebrates. The low-frequency components of the profiles are the residual structure of the sand ripples created by storm waves propagating in the onshore direction. The 1-dimensional roughness power spectrum generated from the 2-dimensional profiles in Fig. 1 shows that the behavior of the spectrum is actually more complex than is indicated by a single value for the spectral slope (Fig. 2). In fact, the slope and intercept values depend on which spatial frequency component is included in the regression. Consequently, the value of spectral slope and intercept used as parameters in acoustic models will depend on the acoustic frequency for which the prediction is to be made.

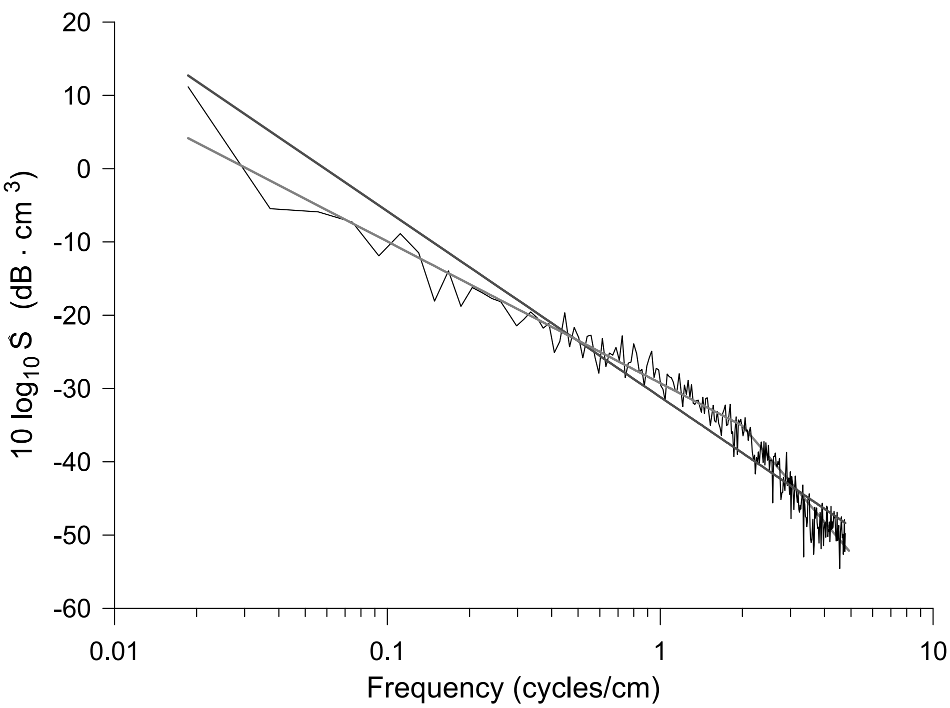

Figure 2. 1-D roughness spectrum estimated for the BAMS site on 23 October 1999. Lighter-shaded lines represent slopes from 0.02 to 2 and 2 to 5 cycles/cm segments of spectrum.

In reference to Fig. 2, predictions made for acoustic frequencies lower than 150 kHz (Bragg wavelength • 0.5 cm) would utilize the portion of the spectrum less than 2 cycles/cm; predictions made for acoustic frequencies higher than 150 kHz would utilize the portion of the spectrum greater than 2 cycles/cm (Table 2). Our results indicate that natural roughness features in shallow-water environments may be *multi-spectral* in character, such that it may be insufficient to characterize the interface roughness with one spectral regression line. Such a divergence of spectral character of seafloor roughness within a spatial frequency range of mm to cm may be a consequence of two different roughness-generating processes: hydrodynamic and biological. Wind-wave currents from storms create the low-frequency roughness realized as ripples. Biological activity on and in the sediment creates high-frequency roughness comprised of tracks, trails, feeding pits, and mounds.

Table 2. Values of roughness spectral slope and intercept for the entire measured spectrum (0.02 to 5.0 cm-1) and the truncated spectra calculated for 4 time periods at the BAMS tower.

Date	Spatial frequency (cm^{-1})	Spectral slope	Spectral intercept (cm^3)
5 Oct.	0.02 to 5.0	-3.16	0.00064
	0.2 to2.0	-3.00	0.00075
	0.02 to 0.2	-3.81	0.00131
19 Oct.	0.02 to 5.0	-2.73	0.00096
	0.2 to2.0	-2.34	0.00137
	0.02 to 0.2	-3.96	0.00378
23 Oct.	0.02 to 5.0	-2.54	0.00077
	0.2 to2.0	-1.94	0.00119
	0.02 to 0.2	-4.39	0.00599
5 Nov.	0.02 to 5.0	-2.53	0.00071
	0.2 to2.0	-2.20	0.00092
	0.02 to 0.2	-3.95	0.00310

IMPACT/APPLICATION

Detection and classification of mines on and in the sea floor is accomplished with high-frequency sound energy: Thus, it is imperative that we understand the factors that control acoustic reverberation from seafloor features as well as the potential for acoustic penetration of the sea floor. From this knowledge, Naval forces may be able to improve mine countermeasures (MCM) capabilities in shallow water. Additionally, the characterization of the environment for SAX99 provides a test bed, or natural laboratory, for future shallow-water acoustic experiments.

TRANSITIONS

The results of this basic research are used in developing acoustic models for seafloor scattering. The database is potentially useful for inclusion in the NAVOCEANO shallow-water MIW sediment database.

RELATED PROJECTS

ONR's Mine Burial Processes (MBP) 6.2 program is indirectly related to this 6.1 research. Predicting burial state of mines on the sea floor is another facet of information, along with the acoustic predictions for scattering strength of seafloor targets, in the decision process in mine hunting.

Ray Lim at Coastal Systems Station, Panama City Beach, FL is involved in developing techniques for modeling acoustic scattering from buried objects, especially including the effects of sediment interface roughness in coupling acoustic energy into the sediment at subcritical grazing angles. Our characterization of the rough interface at SAX99 has a direct bearing on CSS modeling efforts.

ONR is funding Peter Jumars (UMe) and Chris Jones (APL-UW) in a high-frequency acoustic project to study the effects fo benthic biological processes on backscattering. An important component of this research involves photogrammetric determination of temporal roughness variability.

REFERENCES

Chotiros, N.P. (1995) Biot model of sound propagation in water-saturated sand. J. Acoust. Soc. Am., 97:199-214.

Maguer, A., W.L.J. Fox, H. Schmidt, E. Pouliquen and E. Bovio (2000) Mechanisms for subcritical penetration into a sandy bottom: Experiments and modeling results. J. Acoust. Soc. Am. 107:1215-1225.

Richardson, M.D. and K.B. Briggs (1996) In-situ and laboratory geoacoustic measurements in soft mud and hard-packed sand sediments: Implications for high-frequency acoustic propagation and scattering. Geo-Marine Letters 16:196-203.

Richardson, M.D., K.B. Briggs, D.L. Bibee, P.A. Jumars, W.B. Sawyer, D.B. Albert, R.H. Bennett, T.K. Berger, M.J. Buckingham, N.P. Chotiros, P.H. Dahl, N.T. Dewitt, P. Fleischer, R. Flood, C.F. Greenlaw, D.V. Holliday, M.H. Hulbert, M.P. Hutnak, P.D. Jackson, J.S. Jaffe, H.P. Johnson, D.L. Lavoie, A.P. Lyons, C.S. Martens, D.E. McGehee, K.D. Moore, T.H. Orsi, J.N. Piper, R.I. Ray, A.H. Reed, R.F.L. Self, J.L Schmidt, S.G. Schock, F. Simonet, R.D. Stoll, DJ Tang, D.E. Thistle, E.I. Thorsos, D.J. Walter and R.A. Wheatcroft. 2001. An overview of SAX99: environmental considerations. IEEE Journal of Oceanic Engineering 26: 26-53. Thorsos, E.I. (1997) Report on the Office of Naval Research High-Frequency Acoustic Workshop 16-18 April, 1996. Technical Report APL-UW TR 9702.

Thorsos, E.I., Kevin L. Williams, N.P. Chotiros, J.T. Christoff, K.W. Commander, C.F. Greenlaw, D. V. Holliday, D.R. Jackson, J.L. Lopes, D.E. McGehee, M.D. Richardson, J. Piper and D. Tang. 2001. An overview of SAX99: Acoustics measurements. IEEE Journal of Oceanic Engineering 26: 4-25.

PUBLICATIONS

Briggs, K.B. and D. Tang. 2000. Statistical variability of sediment sound speed and density in fine and medium sand. In: M. Zakharia (ed.) Proceedings of the 5th European Conference on Underwater Acoustics, 10-13 July 2000, Lyon, France. European Commission, Brussels, Vol. 2. pps. 1265-1270.

Briggs, K. B. 2000. Spatial and temporal variation of large- and small-scale seafloor roughness. J. Acoust. Soc. Am. 108: 2534.

Briggs, K.B., K.L. Williams, M.D. Richardson, and D.R. Jackson. 2001. Effects of changing roughness on acoustics scattering: (1) natural changes. Proceedings of the Institute of Acoustics, v. 23, Acoustical Oceanography. T.G. Leighton (Ed.), Bath, UK, pp. 375-382.

Briggs, K.B., D. Tang and Kevin L. Williams. submitted. Characterization of interface roughness of rippled sand off Fort Walton Beach, Florida. IEEE J. Oceanic Engineering.

Jackson, P.D., D.A. Gunn and K.B. Briggs. 2000. Assessing 3D volume inhomogeneity using a non-invasive diver deployed resistivity array. J. Acoust. Soc. Am., 108: 2535.

Jackson, D.R. and M. D. Richardson. 2001. Seasonal temperature gradients within a sandy seafloor: implications for acoustic propagation and scattering. Proceedings of the Institute of Acoustics, v. 23, Acoustical Oceanography. T.G. Leighton (Ed.), Bath, UK, pp. 361-368.

Reed, A.H. and D.L. Lavoie. 2000. Quantification of Darcy's coefficient of permeability in siliciclastic marine sands using image analysis and effective medium theory modeling. J. Acoust. Soc. Am. 108: 2535.

Reed, A.H., K.B. Briggs, and D.L. Lavoie. submitted. Sediment porometry of the West Florida Sand Sheet, adjacent to Fort Walton Beach FL from traditional measurements and image analysis/network modeling. IEEE J. Oceanic Engineering.

Richardson, M.D., K.B. Briggs and K.L. Williams. 2000. Biological and hydrodynamic control of seafloor roughness: implications to high-frequency acoustic scattering. J. Acoust. Soc. Am. 108: 2511-2512.

Richardson, M.D., K.B. Briggs, D.L. Bibee, P.A. Jumars, W.B. Sawyer, D.B. Albert, R.H. Bennett, T.K. Berger, M.J. Buckingham, N.P. Chotiros, P.H. Dahl, N.T. Dewitt, P. Fleischer, R. Flood, C.F. Greenlaw, D.V. Holliday, M.H. Hulbert, M.P. Hutnak, P.D. Jackson, J.S. Jaffe, H.P. Johnson, D.L. Lavoie, A.P. Lyons, C.S. Martens, D.E. McGehee, K.D. Moore, T.H. Orsi, J.N. Piper, R.I. Ray, A.H. Reed, R.F.L. Self, J.L Schmidt, S.G. Schock, F. Simonet, R.D. Stoll, DJ Tang, D.E. Thistle, E.I. Thorsos, D.J. Walter and R.A. Wheatcroft. 2001. An overview of SAX99: environmental considerations. IEEE Journal of Oceanic Engineering 26: 26-53.

Richardson, M.D., K.B. Briggs, K.L. Williams, A.P. Lyons, and D.R. Jackson. Effects of changing roughness on acoustic scattering: (2) anthropogenic changes. 2001. Proceedings of the Institute of Acoustics, v. 23, Acoustical Oceanography. T.G. Leighton (Ed.), Bath, UK, pp. 383-390.

Richardson, M.D., K.L. Williams, K.B. Briggs and E.I. Thorsos. submitted. Dynamic measurement of sediment grain compressibility at atmospheric pressure: acoustic implications. IEEE J. Oceanic Engineering.

Thorsos, E.I., K.L. Williams, N.P. Chotiros, J.T. Christoff, K.W. Commander, C.F. Greenlaw, D. V. Holliday, D.R. Jackson, J.L. Lopes, D.E. McGehee, M.D. Richardson, J. Piper and D. Tang. 2001. An overview of SAX99: Acoustics measurements. IEEE Journal of Oceanic Engineering 26: 4-25.

Thorsos, E.I., K.L. Williams, D.R. Jackson, M.D. Richardson, K.B. Briggs, and D. Tang. 2001. An Experiment in High-Frequency Sediment Acoustics: SAX99. Proceedings of the Institute of Acoustics, v. 23, Acoustical Oceanography. T.G. Leighton (Ed.), Bath, UK, pp. 344-354.

Williams, K.L., M.D. Richardson, K.B. Briggs and D.R. Jackson. 2001. Scattering of high-frequency acoustic energy from discrete scatterers on the seafloor: glass spheres and shells. Proceedings of the Institute of Acoustics, v. 23, Acoustical Oceanography. T.G. Leighton (Ed.), Bath, UK, pp. 369-374.